

Modular Advanced Composite Hull-form (MACH) Technology

Progress Report Period June-September 2001

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TABLE OF CONTENTS

	Page
1. Introduction.....	1
1.1 Objectives.....	1
1.2 Current Work	1
2. Connection Concept Development and Evaluation.	2
2.1 Identification of Viable Connections.....	2
2.2 Connection Concepts Groupings.....	2
2.3 Evaluation Factor Criteria.....	3
2.4 Connection Concepts.....	5
2.4.1 Bolted Laminate Connections	5
2.5 Evaluation of Connection Concepts.	19
2.5.1 Bolted Laminate Connections.	19
2.5.2 Bolted Close-Out Connections.	19
2.5.3 Co-cured Connection with Metallic Inserts	20
2.5.4 Metallic Extension w/ Secondary Bond.....	20
2.5.5 Integral Fit (Mechanical Locking).....	20
3. Structural Monitoring	21
3.1 Fiber Optic Strain Sensing	21
3.1.1 Methodology.....	21
3.2 Piezoelectric Sensing	22
3.3 Data Processing and Networking	22
4. HYSWAC Development.	23
4.1 Cavitation Erosion of Underwater Hulls.....	23
5. Summary and Conclusions	23

1. Introduction

This progress report for the project Modular Advanced Composite Hullform (MACH) Technology covers the period from June 2001 to September 2001. The University of Maine (UMaine) has organized a coalition of University, Industry and Navy partners to develop innovative modular hull constructions techniques for fast surface ship and hybrid hull applications. In this effort the University of Maine is partnered with Pacific Marine & Supply Co of Honolulu, HI (PACMAR), a pioneer in advanced ship hull form development, Applied Thermal Sciences Inc of Sanford, ME (ATS), an engineering research and development consulting company with extensive experience in innovative DoD projects, Nigel Gee and Associates of Southampton, UK, (NGA) a marine architecture firm with extensive experience in high speed vessel design. Technical expertise will be brought from the, NAVSEA Surface Warfare Center Bethesda, MD (NSWC-CD), Naval Sea Systems Command Undersea Warfare Center Newport, RI (NAVSEA Newport) and other organizations are and will be technical consultants throughout the program.

1.1 Objectives

The long-term objective of the proposed program is to develop and demonstrate hybrid composite /metallic structure joining concepts and technology for application to naval ship hulls. It is envisioned to develop hybrid joint concepts and technology that will have as broad of impact as possible on Navy vessels. The technology will be investigated for two types of generic hybrid construction: (a) the out-of-plane attachment of dissimilar composite and metallic structure (e.g., the attachment of composite panels to a supporting metallic framework) for the HYbrid Small Waterpalne Area Craft (HYSWAC) and (b), the in-plane attachment of dissimilar metallic and composite structure for the hybrid hull (e.g., the attachment or connection for a hybrid composite to metallic ship hull structure). The technology will be demonstrated at both the joint component level and at the hybrid system level. As a secondary objective, the smart skin concept for structural monitoring will be investigated as part of MACH, and the HYSWAC structural monitoring system will leverage the results.

1.2 Current Work

The primary tasks undertaken during this period include:

1. Development of concepts and criteria for hybrid structure and connections.
2. Develop criteria for structural monitoring system.
3. Design of underwater body for the HYSWAC.

2. Connection Concept Development and Evaluation.

Work thus far on connections is summarized as follows:

1. Identification of feasible connections type.
2. Cataloging of the connection details and dividing into groups for evaluation.
3. Evaluation of the connections.
4. Identification of research issues.

2.1 Identification of Viable Connections

A series of connection concepts were identified through an extensive review of the literature. The concept generation was achieved through a review of existing connection systems and brainstorming sessions. Preliminary joint selection was performed through an evaluation of current joint systems. The joint systems were first categorized, and then evaluated, by the research teams at UMaine, NSWC-CD, and ATS. A total of 20+ joint systems were categorized and evaluated.

2.2 Connection Concepts Groupings

Cataloging of connections was limited to possible alternatives that may provide the desired capability. The connection types, identified to date are sorted into connection concept groups as follows;

1. **Bolted Laminate Connections:** Thick or thin laminates attached by bolts directly to framing. Can be adapted to single shell, stiffened or sandwich composites. Alignment of bolt holes is crucial to a properly loaded joint.
2. **Bolted Close-Out:** The bolted close-out concept incorporates an adhered metallic endcap (close-out) to the end of the laminate, which is then bolted or welded to the sub-framing.
3. **Co-cured Metallic Insert:** This concept utilizes the molding process to embed a metallic connector into the composite laminate creating a primary bond between the composite and metal insert. The assemblage can be bolted or welded to the sub-framing.
4. **Metallic Extension w/ Secondary Bond:** This group of joints use an adhered metallic end cap that is solid at the joint. This type of connection eliminates the concerns of bolt shear and clamping effects that can occur with composite laminates over time, since a metal-to-metal connection is used.

5. **Integral Fit (Mechanical Locking)**: Integral fit connections rely on the shape of the parts to create a mechanical lock when they are connected together.

2.3 Evaluation Factor Criteria

A system of evaluation factors has been preliminarily identified as a means to evaluate each connection concept relative to each other. Feasible concepts are to be evaluated for their weight, cost / manufacturability, structural performance, environmental performance, and operability.

2.3.1 Weight: The joint/panel concepts will be developed to reduced weight over conventional construction. The weight reduction goal for these hybrid concepts is desired to be 25-30% or more over an all metallic configuration.

2.3.2 Cost / Manufacturability: The joint/panel concepts will be developed to be cost competitive with conventional construction and designed to be manufactured by current manufacturing practices endorsed by the Navy such as an open-mold vacuum assisted resin transfer method, namely VARTM, SCRIMP, etc. The panels will be designed for high volume and mass production and at lowest possible costs.

2.3.3 Structural Performance: The joint/panel concepts will be designed to meet Navy requirements and to conform with ABS standards for frame and stiffener spacings. These concepts will be subjected to various loading conditions, which include quasi-static seaway induced conditions as well as dynamic shock loads. Failure theories such as Tsai-Wu, maximum stress, maximum strain and others will be used during the analysis phase to assess safety factors.

2.3.4 Environmental Performance: The joint/panel concepts will be watertight over required life cycles. Galvanic corrosion will not occur between the metallic components and the mechanical fasteners. The materials in the joint/panel concept, including any bond-line adhesives, will meet long-term durability requirements.

2.3.5 Operability: For removable panels, the objective of the joint/panel design is to remove the panels at or below the waterline in a dry-dock facility. A class of semi-removable panels will also be considered for locations where access to equipment is not necessary.

These concepts are evaluated on a consensus of engineering judgment of the MACH team. The proposed evaluation matrix and weight factors are summarized in Table 2.1. Scores are from 0 to 5; the higher the score the better. The concepts are scored on a relative sense within the respective categories. A weighting factor is assigned to each of the score factors depending on the significance of the factor to the connection performance and the availability of the information. These weighing factors (0 to 10, 10

being most important) will be multiplied by each concept score to provide the weighted totals for the concepts.

Table 2.1 – Evaluation Matrix for Connector Concepts

Evaluation of the Recommended Connection Method				
Factors	Weight	Concept: _____		
		Unweighted	Weighted	Remarks
Weight	6			
Cost Manufacturability	8			
Structural Performance	10			
Environmental Performance	10			
Operability	6			
TOTAL		0	0	
COMMENTS:				

2.4 Connection Concepts

2.4.1 Bolted Laminate Connections

Thick laminates are generally easier to attach directly to framing than sandwich composites are, but fastener selection and alignment are crucial to a properly loaded joint. Loss of bolt stress due to viscoelastic creep in the composites is a major concern in this type of application. If the concept involves a stiffened laminate, the laminate will be thinner than in a monocoque design and may require ply reinforcement in the bolted region as shown in Figure 2.1. This is accomplished internally, during the manufacturing process, or externally as a secondary bonding process.

Research Areas (Specific to this Concept):

3D Fiber architecture in the vicinity of the connection can be used to lessen the creep effect. The effects of laminate thickness, laminate schedule, ply drop-off, and fastener selection on the structural integrity of the connection need to be determined. Effect of discrete inserts can also be investigated. Fastener corrosion must also be avoided.

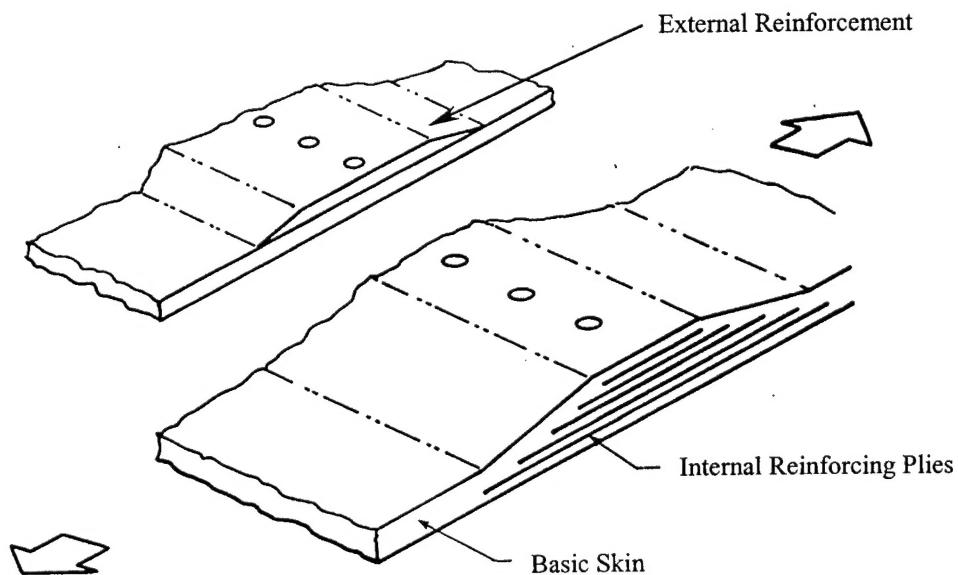
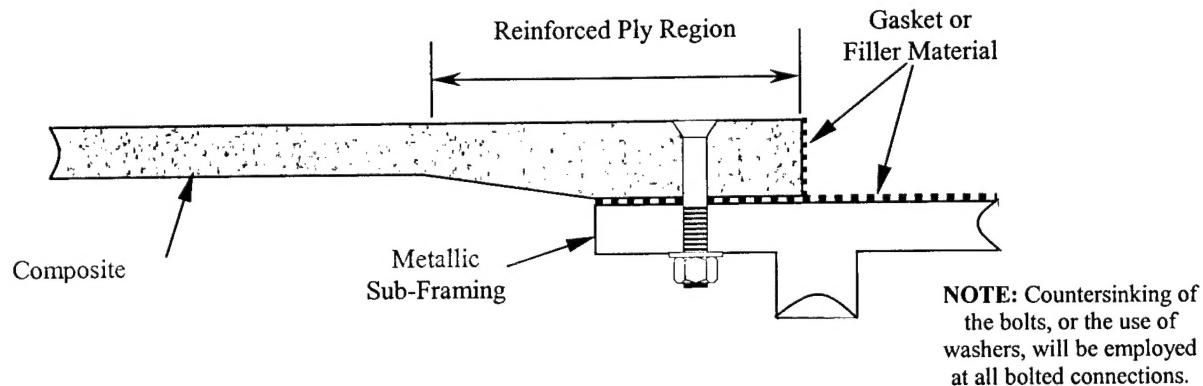
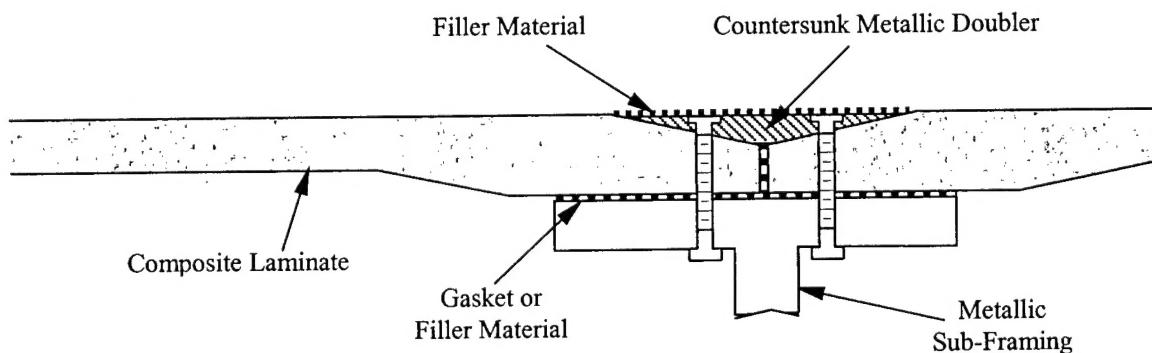


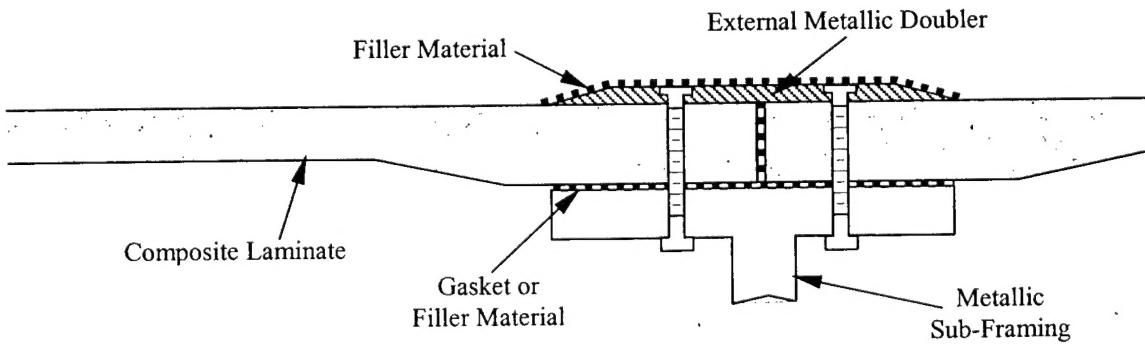
Figure 2.1 Ply Reinforcement in Connection Region



Concept 1.1 Bolted Laminate Connection



Concept 1.2 Bolted Laminate Connection



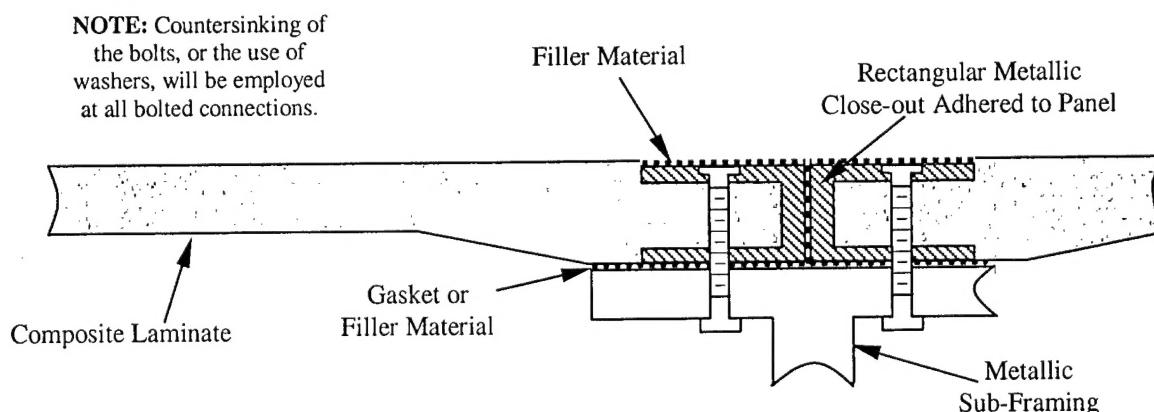
Concept 1.3 Bolted Laminate Connection

2.4.2 Bolted Close-Out

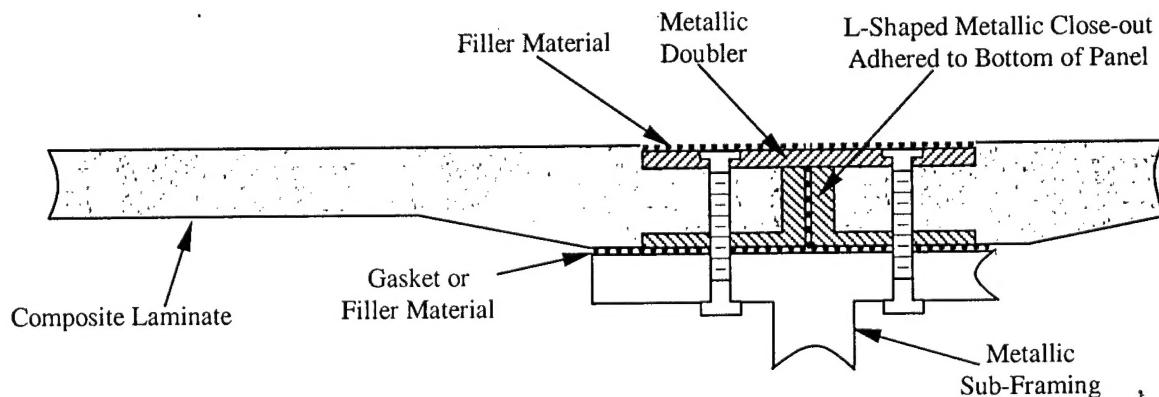
The bolted close-out concept incorporates an adhered endcap (close-out) to the end of the laminate, which is then bolted to the sub-framing. The close-out better distributes the clamping force into the laminate to lessen the effect of bolt stress relaxation due to creep in the composite material. Potential joint candidates are given in the figures below.

Research Areas (Specific to this Concept):

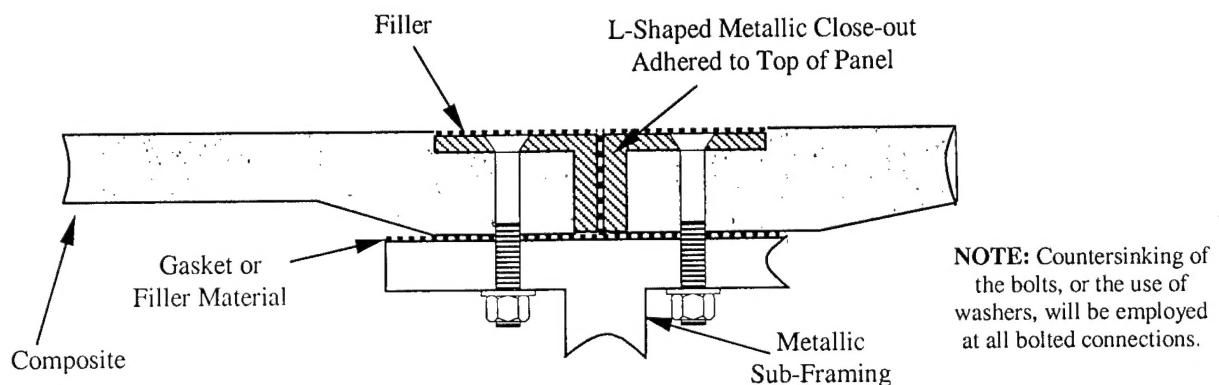
The effects of close-out geometry, adhesive, and laminate thickness, on structural integrity need to be studied. The use of 3D reinforcements as a means of creep reduction can also be investigated.



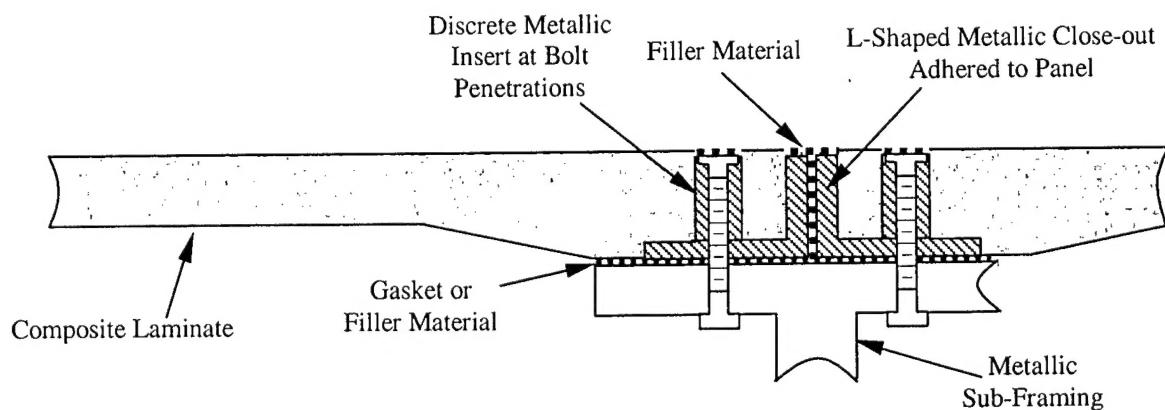
Concept 2.1 Rectangular Metallic Close-out



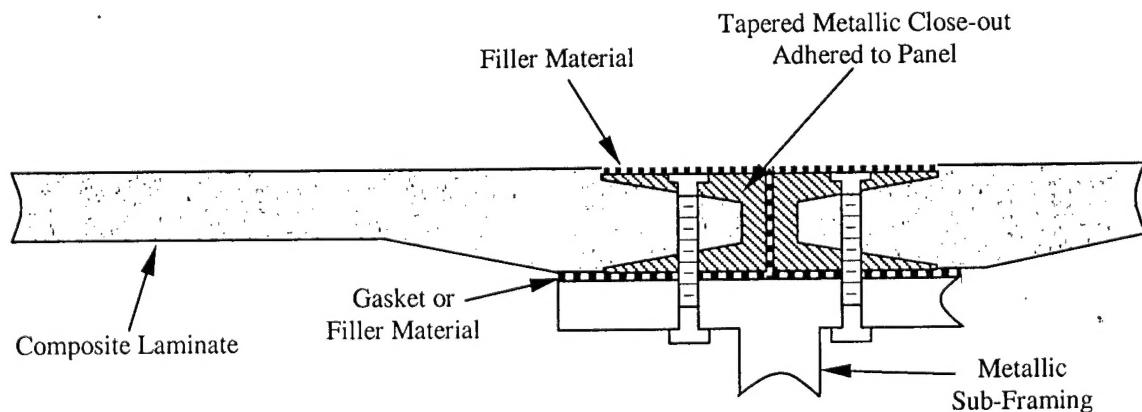
Concept 2.2 L-Shaped Metallic Close-out w/ Doubler



Concept 2.3 L-Shaped Metallic Close-out



Concept 2.4 L-Shaped Close-out w/ Insert



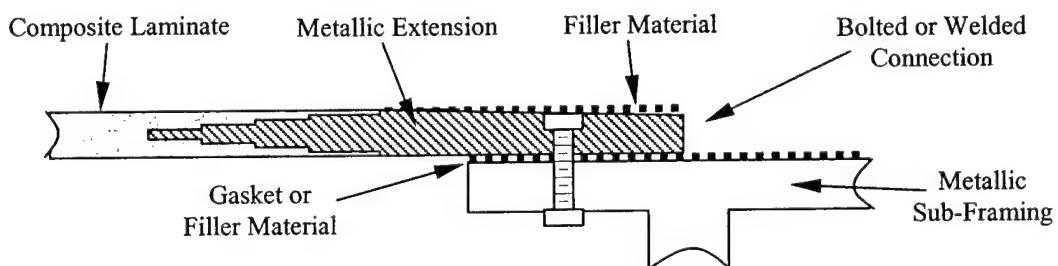
Concept 2.5 Tapered Metallic Close-out

2.4.3 Co-cured Metallic Insert

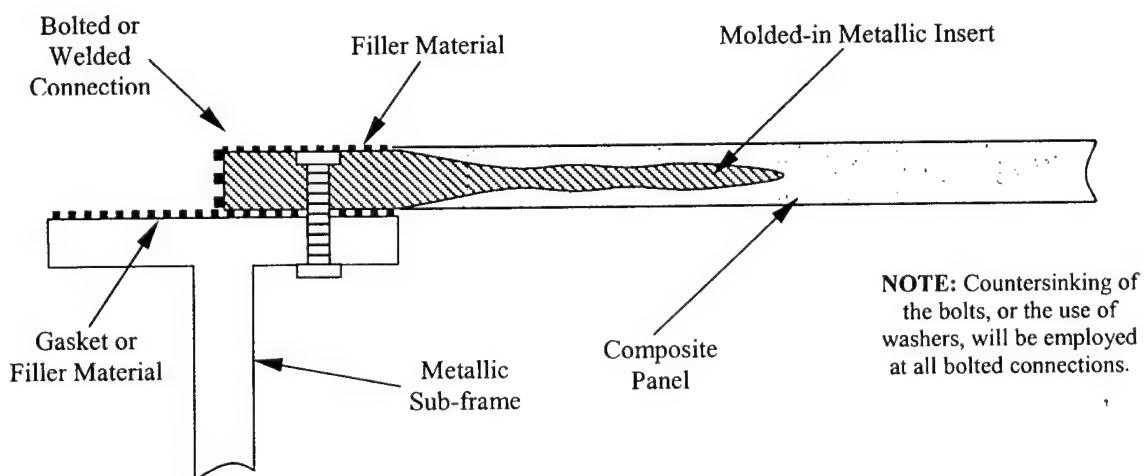
This concept utilizes the molding process to embed a metallic connector into the composite laminate creating a primary bond between the composite and metal insert. The inserts can be continuous along the panel edges or at discrete locations. The resulting panel to frame connection is a bolted metal-to-metal connection. One of the advantages of this concept is that it incorporates the metallic insert into the manufacturing stage with little complication to the manufacturing process. Another advantage is that only the metal surface requires machining. Potential joint concepts are shown in the figures that follow.

Research Areas (Specific to this Concept):

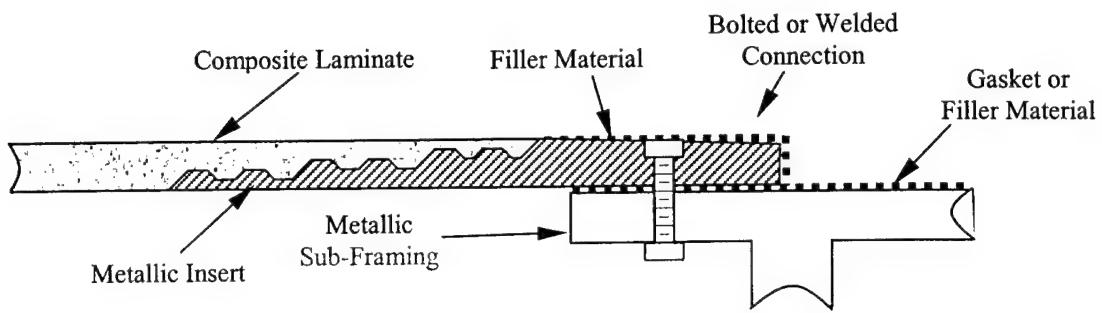
The effects of insert geometry and laminate thickness, on structural integrity, need to be determined. Deformations during the curing cycle, due to differences in the CTE of the materials, needs to be studied. Resin selection and metallic surface preparation are key to a proper bond of the components.



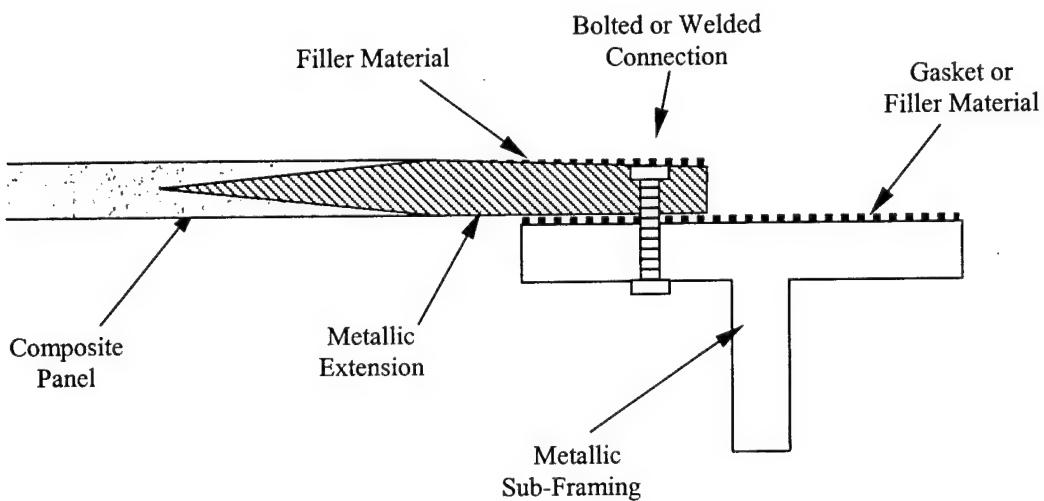
Concept 3.1 Step-lapped Molded-in Metallic Insert



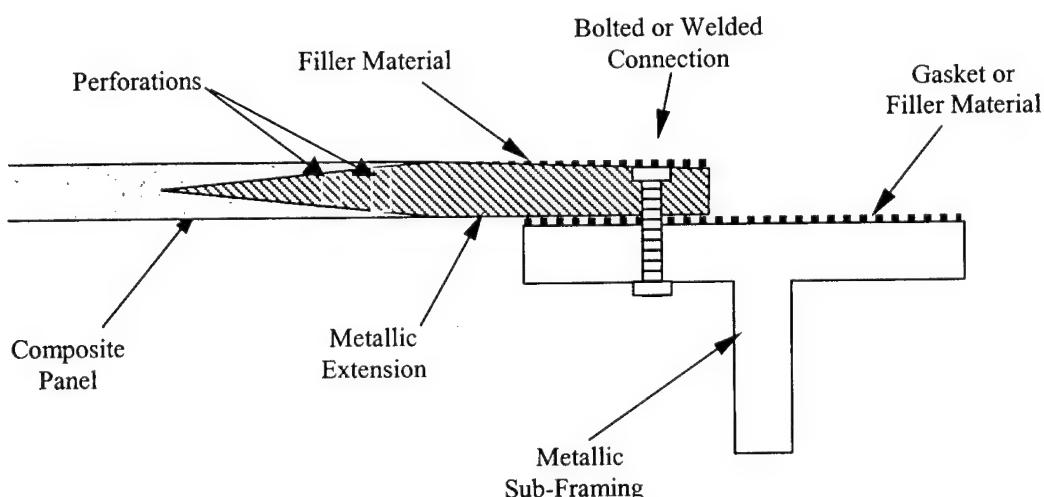
Concept 3.2 Dog-Boned Molded-in Metallic Insert



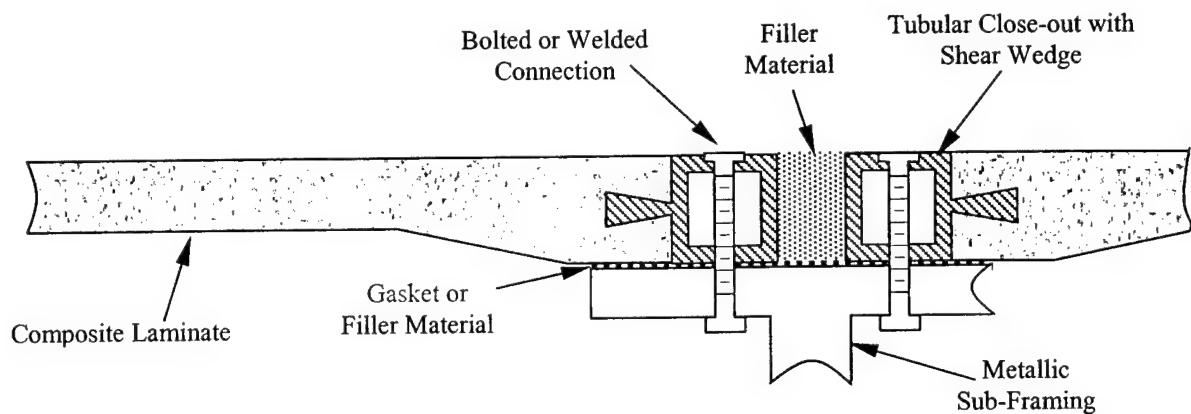
Concept 3.3 Ribbed Molded-in Metallic Insert



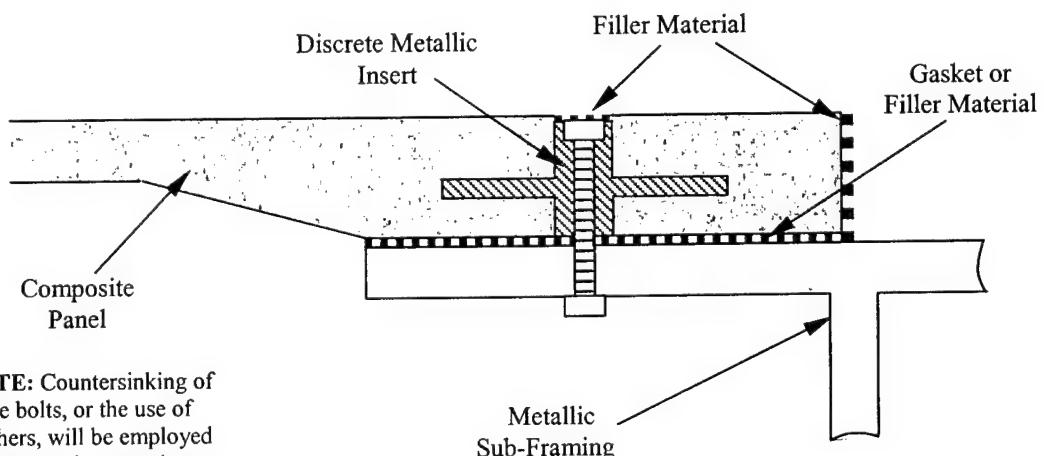
Concept 3.4 Uniformly Tapered Molded-in Metallic Insert



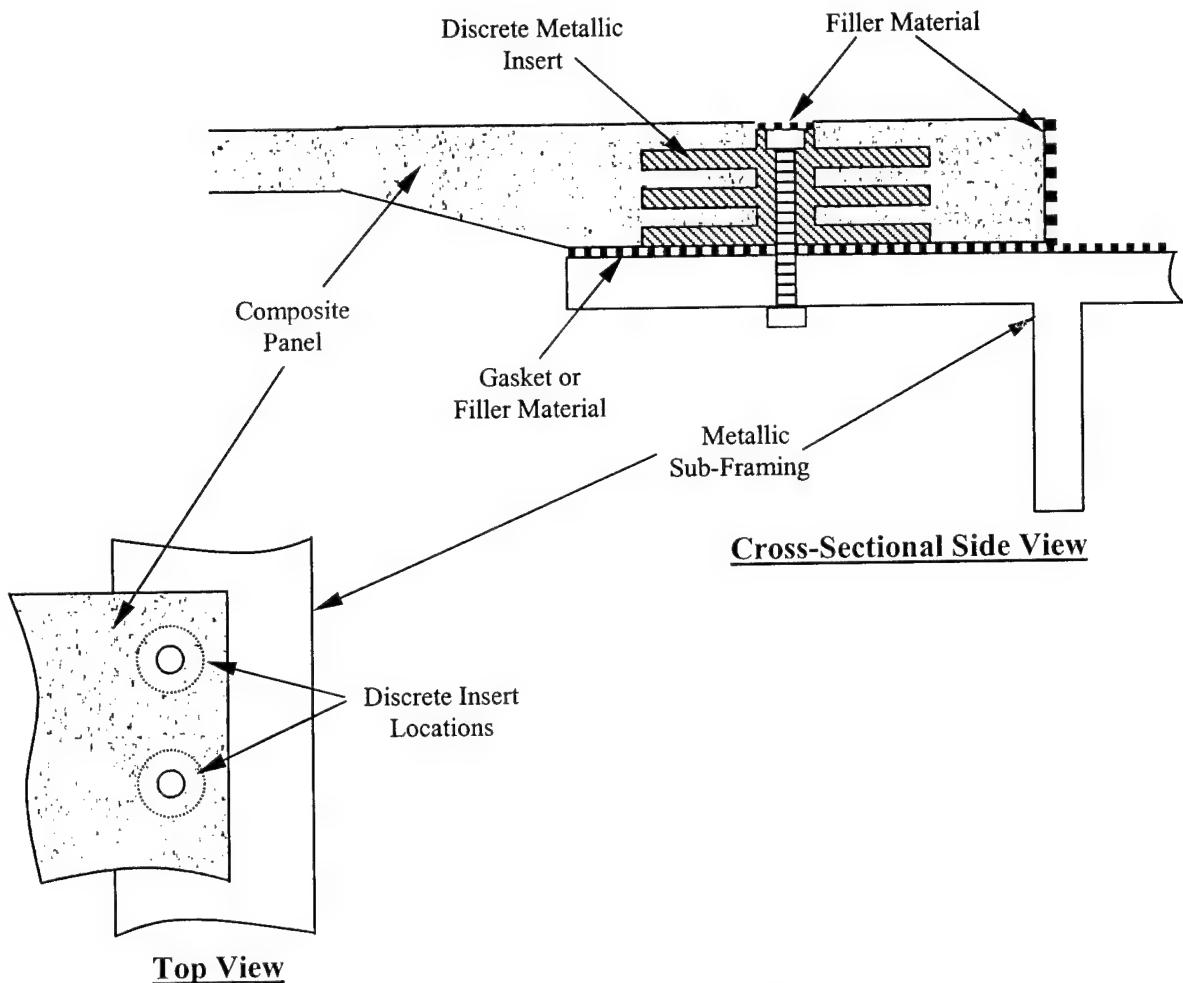
Concept 3.5 Perforated Metallic Insert



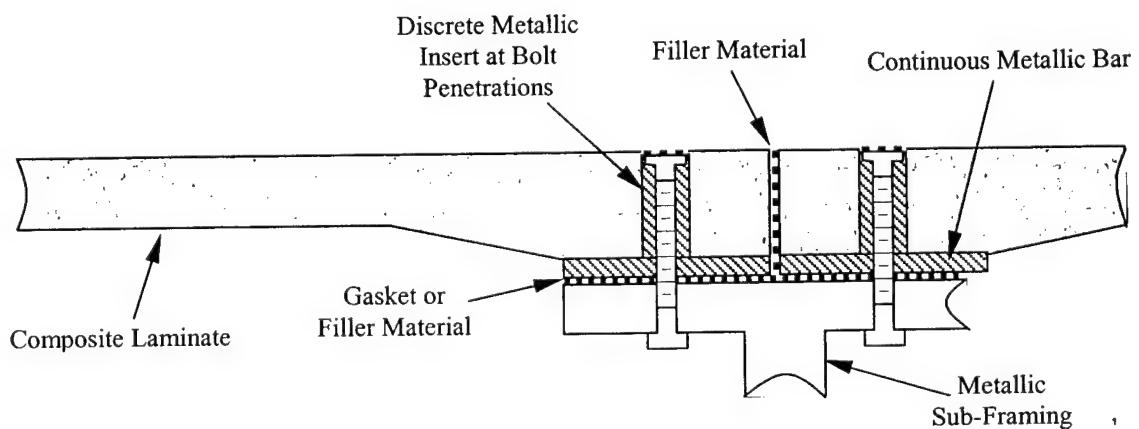
Concept 3.6 Tubular Close-out w/Shear Wedge



Concept 3A.1 Discrete Molded-in Metallic Insert Concept



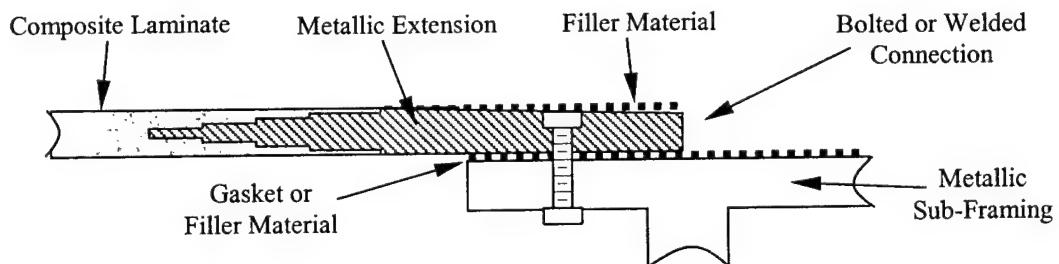
Concept 3A.2 Discrete Molded-in Metallic Insert Concept



Concept 3A.3 Discrete Insert w/ Continuous Bar

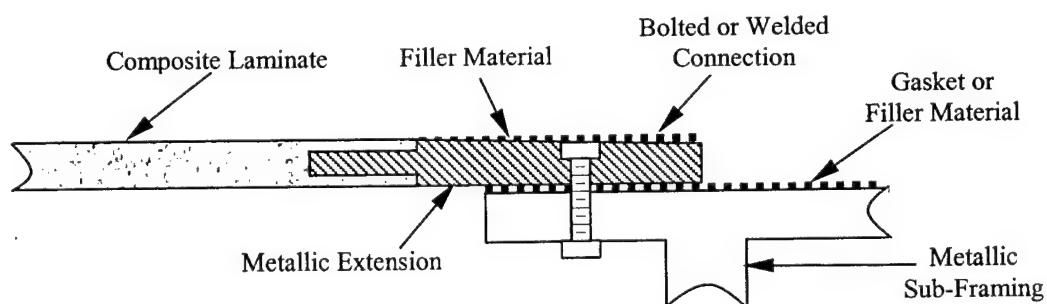
2.4.4 Metallic Extension w/ Secondary Bond

This type of connection eliminates the concerns of bolt shear and clamping effects that can occur with composite laminates over time, since a metal-to-metal connection is used. An advantage of this concept is that it allows for bolted or welded connections to the sub-framing. Possible configurations are shown in the figures below. The stepped lap joint in Concept 4.1 is used extensively for attaching composite tail and wings sections on military aircraft. It has excellent mechanical properties in tension and bending but requires extensive machining of both metal and composite interfaces. This is a distinct disadvantage for curved panel connections. Since thick laminates require some form of multi-step increment in thickness, for proper adherence of the components, the tongue & groove, step, or a double scarf configuration may prove more economical for the curved panels.

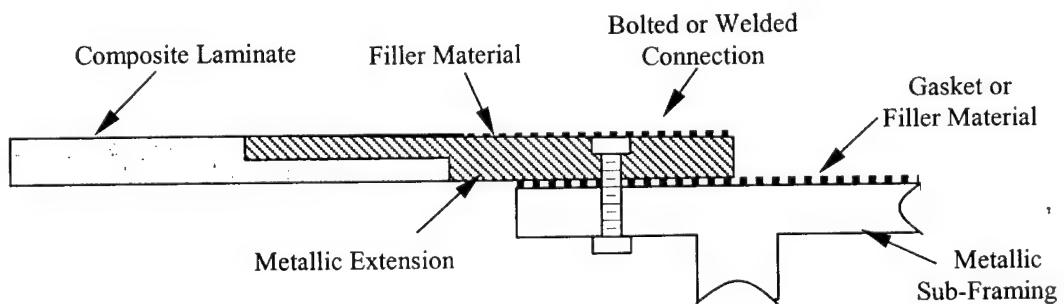


Concept 4.1 Stepped lap-joint used for attaching metallic inserts to thick laminates

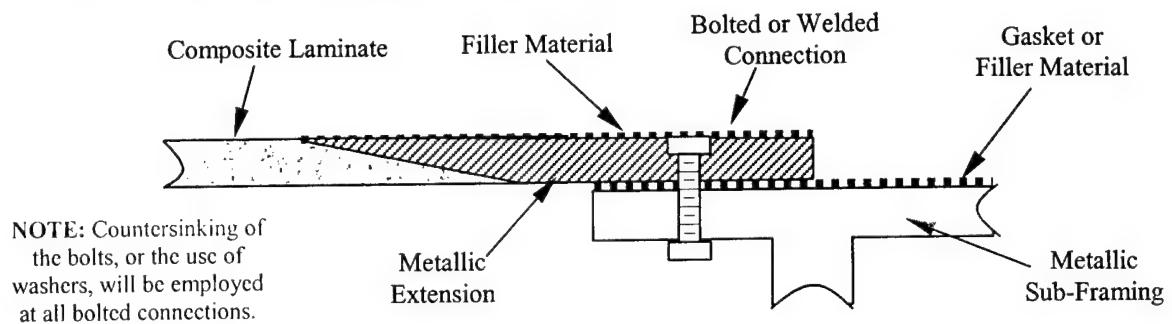
NOTE: Countersinking of the bolts, or the use of washers, will be employed at all bolted connections.



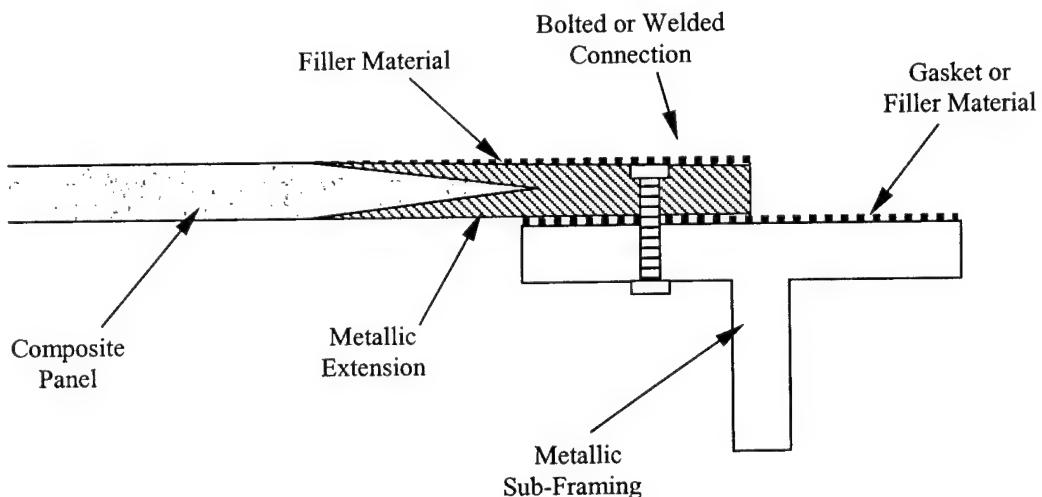
Concept 4.2 Tongue & groove joint for attaching metallic inserts to thick laminates



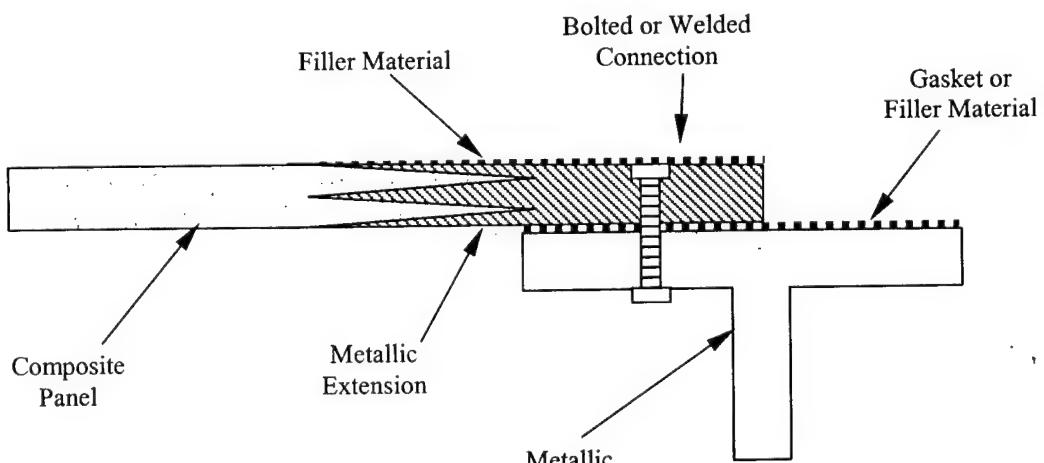
Concept 4.3 Step-lap joint for attaching metallic inserts to thick laminates



Concept 4.4 Scarf joint for attaching laminates to metal



Concept 4.5 Double-Scarf joint for attaching laminates to metal



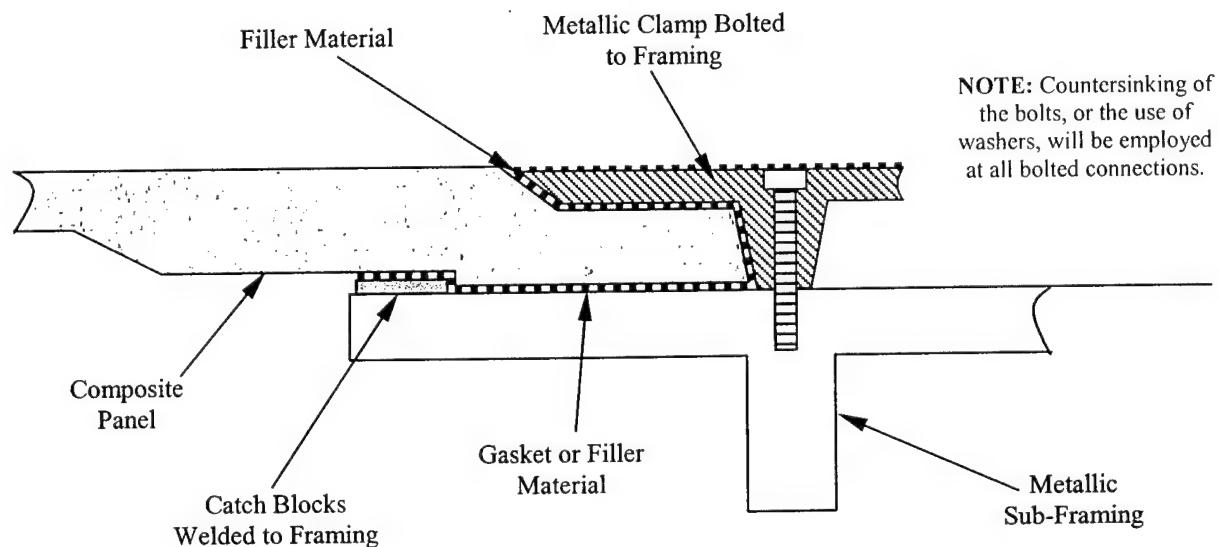
Concept 4.6 Saw-Tooth joint for attaching laminates to metal

2.4.5 Integral Fit (Mechanical Locking)

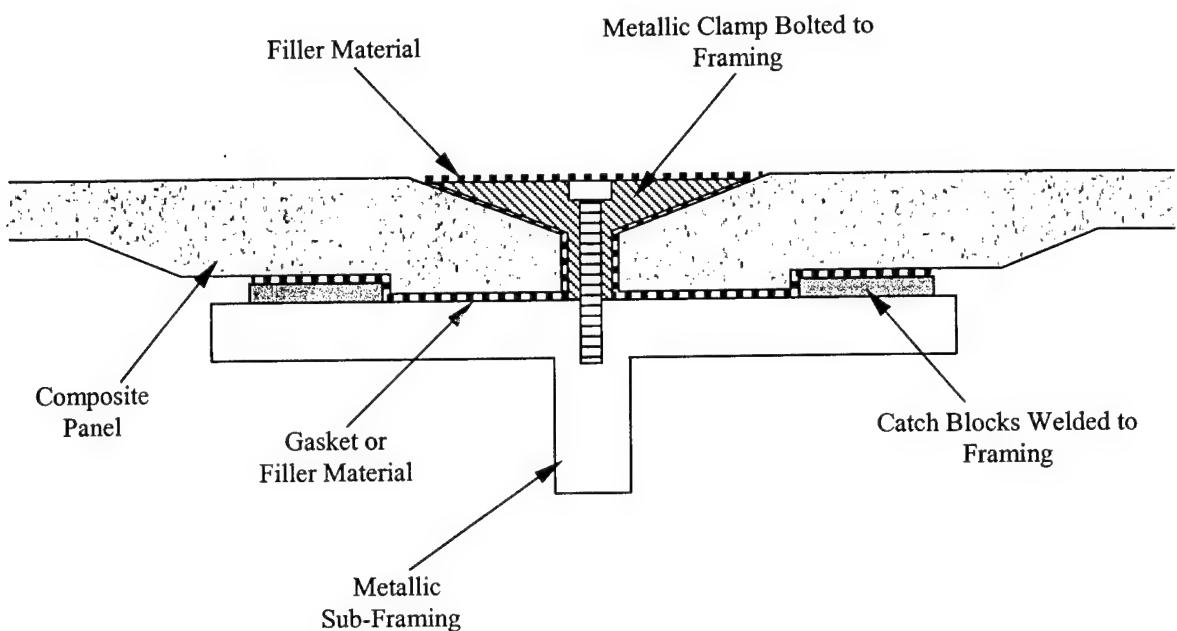
Integral fit connections rely on the shape of the parts to create a mechanical lock when they are connected together. The advantages of an integral fit connection include the potential for reduced assembly time and the avoidance of the deleterious effects that bolting through the panel introduces into the composite laminate. A disadvantage is that the geometry of the parts tends to be more complex. Potential joint geometries are shown in Concepts 5.1-5.4.

Research Areas (Specific to this Concept):

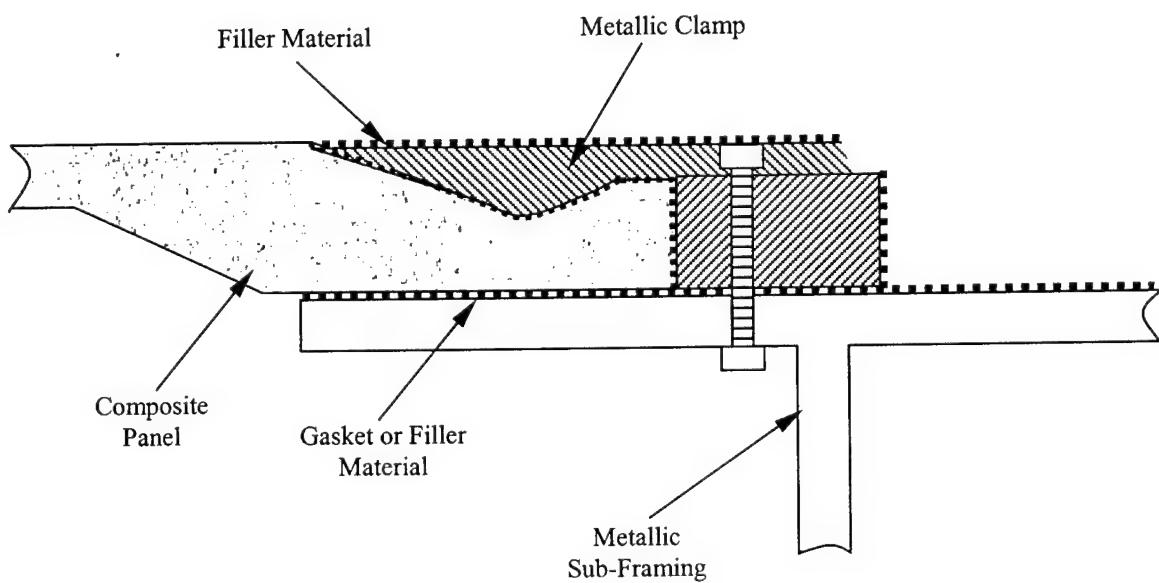
The proper connection geometry, which creates a structurally sound and watertight connection that also allows for manufacturing tolerances must be developed.



Concept 5.1 Integral Fit Connection Concept

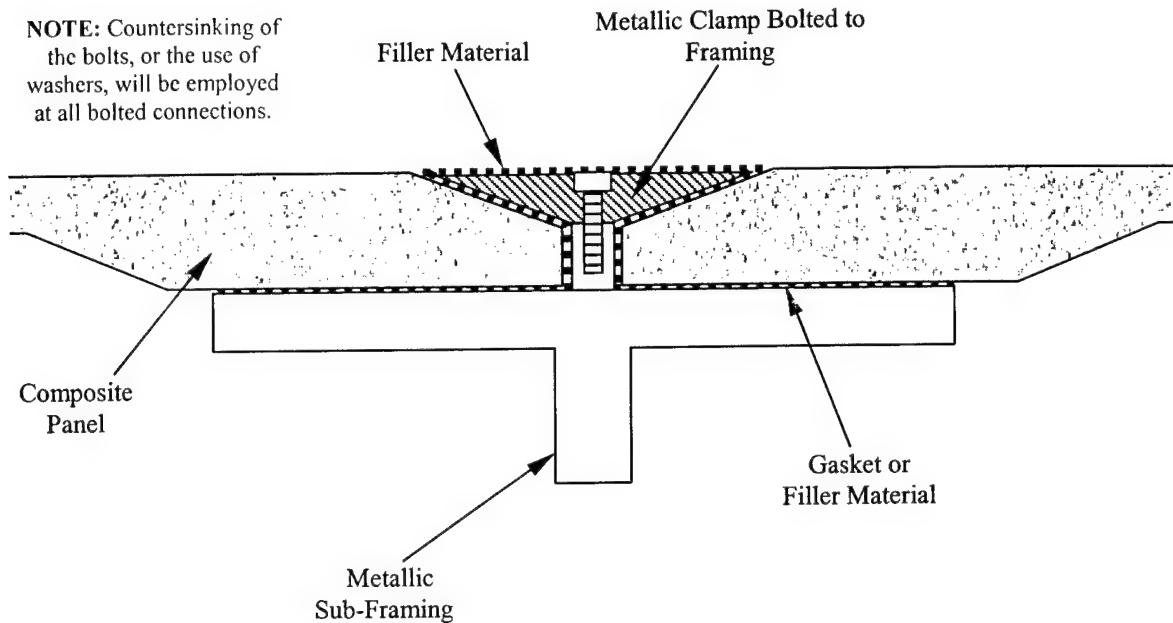


Concept 5.2 Integral Fit Connection Concept



Concept 5.3 Integral Fit Connection Concept

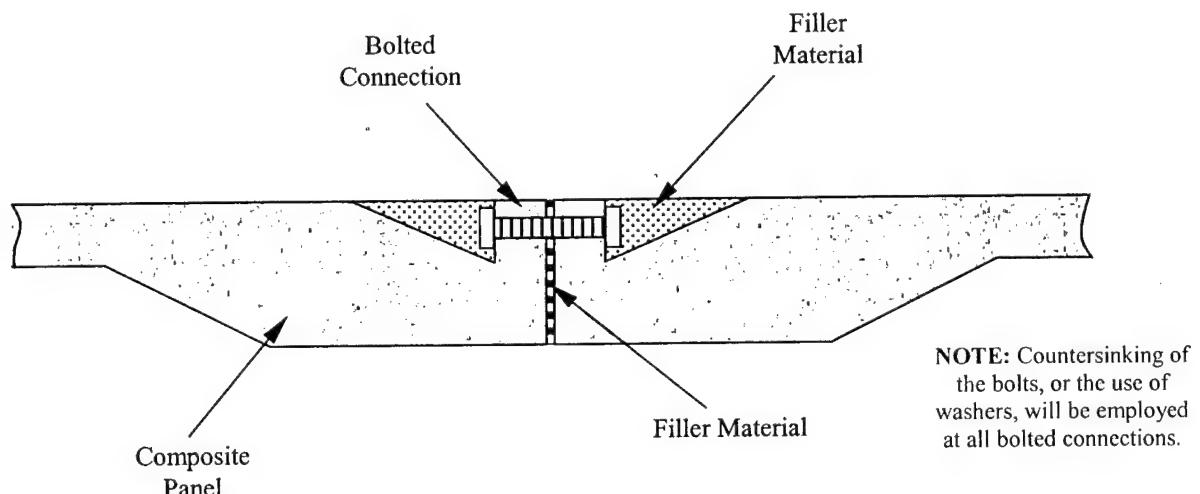
NOTE: Countersinking of the bolts, or the use of washers, will be employed at all bolted connections.



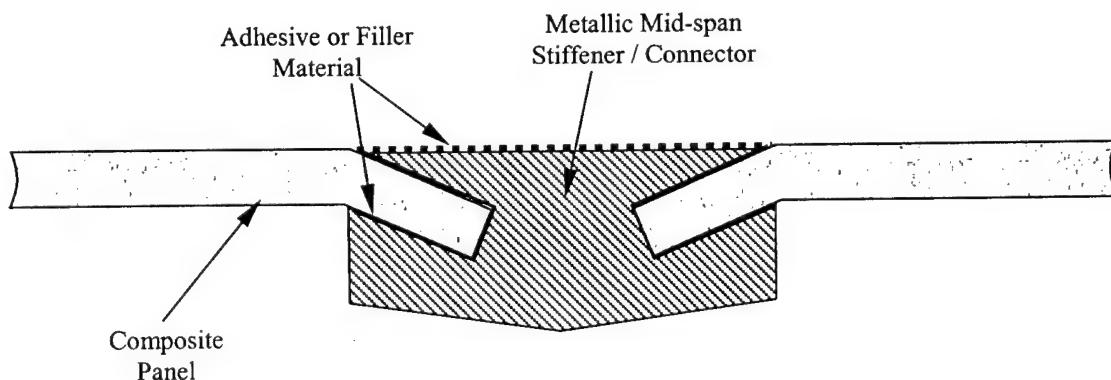
Concept 5.4 Integral Fit Connection Concept

2.3.6 Frameless (Mid-Span)

The frameless connection concept uses a stiffener region, made of composite or metal, to bridge the gap between the metallic sub-frame. This would allow larger regions of the hull to be opened for equipment removal. Potential concepts are shown below in Concepts 6.1 & 6.2.



Concept 6.1 Frameless Panel Connection Concept



Concept 6.2 Metallic Stiffener Frameless Connection Concept

2.5 Evaluation of Connection Concepts.

Connection concepts were first evaluated individually by V. Caccese, R. Bragg, and K. Berube at UMaine, L. Thompson at ATS, and L. Nguyen, M. Crichfield and G. Camponeschi at NSWC-CD. A group meeting was conducted in September where the evaluations were compiled and a decision was made as to program focus in regard to hybrid connections. Pertinent research issues were discussed at this meeting and are summarized in the remainder of Section 2.5.

Connections that are lightweight and with simpler details will be the most cost effective. If issues regarding the simpler joints can be mitigated then a sensible approach to joint selection is to use the simplest joint possible. Bolted connections received the highest rating primarily due to their cost effectiveness. Therefore, research on issues related to bolted connections with watertight integrity should be accelerated. A program for studying stress relaxation in bolted joints should be carried out.

2.5.1 Bolted Laminate Connections.

The bolted laminate connection was thought to be the most economical. It is simple, lightweight, low cost, adhesive is not an issue and it is simple to model and scale. The primary issue with this type of connection is potential for reduction in watertight integrity due to relaxation in bolt stress caused by creep of the composite material. This may result in poor structural performance. Mitigation of this issue may need to include complicated layup at the connection region or implementation of relatively expensive inserts.

An assessment of the torque required to keep a connection watertight is recommended for study. A review of literature uncovered very little information regarding creep through the thickness in an Eglass/Vinylester composite. A decision was mad to embark on an experimental program to study this effect.

2.5.2 Bolted Close-Out Connections.

The bolted close-out connection has potential to reduce stress relaxation by reducing local stress concentrations and shifting some of the bolt load through metallic components. It also may allow for a welded connection to the sub-frame. This will result in a better than average structural performance and a good ability to maintain watertight integrity. One of the primary issues with this group of connections is cost especially when panels are highly curves. This may be overcome by research on innovative manufacturing techniques.

This connection relies upon an adhesive bond between the composite to metal for a good portion of the structural integrity. Curved panels made of this type of joint may be costly. Tolerances are expected to be more typical of naval applications ranging in tenths of inch not hundredths. Choice of adhesive, environmental effects, and variation in bondline

thickness were identified as critical issues. A decision was made to embark on an experimental program to study this effect.

Other issues discussed regarding this connection were related to corrosion of the metallic components. Corrosion protection needs to be incorporated into design details.

Analysis of this joint with FEA would prove beneficial especially in assessing the effect of relative stiffness of the metallic and composite parts. Use of welded close-outs was also discussed as a potential means of creating a watertight seal. The weld needs to have a minimum standoff distance from the composite so that the composite is not affected by the heat from welding.

2.5.3 Co-cured Connection with Metallic Inserts

Some advantages of this connection type is that they eliminate concerns due to bolt stress relaxation, and can be welded to the sub-frame if detailed appropriately. This connection may be good for well-defined loading. Details and manufacturing of this connection type were identified as critical issues. There is much that can be done creatively with connections of this group. The effect that specific details and manufacturing techniques have on overall structural performance is unknown. A decision was made to embark upon manufacturing studies of these joints.

2.5.4 Metallic Extension w/ Secondary Bond

Some advantages of this connection type is that they eliminate concerns due to bolt stress relaxation, and has the ability to weld to the sub-frame. This system relies heavily on adhesive bonding and the study being carried out for the close-out connections will also apply to this class of joints. The cost to manufacture is expected to be high due to extensive machining requirements. The weight is expected to be high also due to the solid metallic parts. Another drawback pointed out with this connection is low shear capacity.

2.5.5 Integral Fit (Mechanical Locking)

The primary issues with integral fit type connections is with respect to their response under dynamic load and their complexity. The connection may become unstable when the load is reversed. It was decided to forgo research on this type of connection at the present time.

3. Structural Monitoring

As part of the MACH effort structural monitoring techniques will be developed specific to composite material usage in hybrid joints and underwater bodies. One purpose of structural monitoring is to determine operational condition of the structure.

Structural Monitoring work was accomplished in three primary areas as follows:

1. Fiber optic sensors for strain measurements
2. Piezoelectric sensors using designs that allow for embedment in curved structures
3. Data processing and networking techniques

3.1 Fiber Optic Strain Sensing

The scope of the research on fiber optic sensing is to develop a methodology for embedding sensors in fiber-reinforced composite materials for monitoring strains and moisture content during manufacturing and under service conditions. Thus, the objectives for this research are as follows:

1. Learn and experiment with techniques on how to embed sensors that will provide required strain data and detect the presence of moisture.
2. Evaluate the reliability and durability of embedded sensors.
3. Establish the effect of embedding sensors on composite properties and structural integrity.
4. Initially an extensive literary review was performed to determine current information on the subjects of fiber optic sensor technology and embedment techniques. This information was used to purchase a fiber optic sensing system (monitoring system and sensors) from Luna Innovations and was also used to develop embedment methods.
5. Next several manufacturing processes were investigated to determine a process that could produce panels with very similar engineering properties. This investigation was necessary so that material variability could be reduced. All test coupon panels will be fabricated using the Seemann's Composite Resin Infusion Molding Process (SCRIMP) as this process produces high quality panels with reduced defects.

3.1.1 Methodology

To achieve the above objectives questions were posed and a method to answer those questions was proposed. The following section contain the questions asked and the methods proposed to get to the above objectives:

1. How to embed sensors so that negative effects on composite material properties can be minimized?
2. Will fiber optics bond with reinforcement and matrix so that strain data is of host material?

3. How to prevent destruction of fiber-optic leads at the location of ingress/egress with host material?
4. How to embed sensors so that they are not damaged by the testing mechanisms?
5. If sensors are embedded not parallel to the reinforcement orientation, how precise is the data gathered in comparison to conventional strain gages?

6. Where should moisture sensors be embedded to provide an early warning system for structural integrity?
7. Should moisture sensors be embedded in hybrid coupons or sandwich coupons or both to simulate actual structure?
8. How do we simulate real world, long-term environmental conditions on test coupon?

3.2 Piezoelectric Sensing

The goal of this effort is to develop techniques for embedment of flexible piezoelectric sensors/actuators into curved composite panels. A new class of piezoelectric sensor is emerging that are much more flexible in nature than the typical piezoelectric patch. This allows for the possibility of embedment in highly curved structures. The flexible piezoelectric patches can be used as both sensors and actuators therefore they are more versatile than elements that sense only. Due to their capacitive nature they can only be used to measure dynamic strain, which is one drawback.

Preliminary work here consists of identifying a supplier for flexible piezoelectric elements, designing a system for testing the effectiveness of the sensing elements.

3.3 Data Processing and Networking

The purpose of the data processing system is to establish a network of processors with a variety of sensors and actuators and to communicate using a variety of TCP/IP protocols. In so doing a reduction of network wiring is anticipated along with the creation of reusable software routines.

The goals of this effort are as follows:

1. The ability to control and monitor numerous sensors on or in a panel.
2. The number of external connections should be small.
3. The physical size of any circuitry should be small.
4. The system should be suited to a wide variety of sensors
5. The system should connect to the external world in a simple way.

Criteria for choice of Microcontroller for this effort is based upon: Low cost; High speed; Low power; Large number of I/O lines; Networkable.

4. HYSWAC Development.

Coordination with Nigel Gee Associates for the detail design of the HYSWAC underwater body was carried out. At the end of the first report period 75% of the FEA was completed including structural arrangements of the lower hull and ship connections. Details of the structural design are anticipated in the second quarter.

Fabrication using different construction methods was investigated. The issue of cavitation erosion protection was addressed.

4.1 Cavitation Erosion of Underwater Hulls

Cavitation erosion of underwater hulls was identified as a necessary area of research. There is potential for this to become a major issue for underwater bodies at speeds required to achieve future design goals. A decision was made to commence a study on systems for cavitation erosion protection with ATS as the lead for this effort.

5. Summary and Conclusions

Numerous connection concepts were surveyed and categorized during this period. An evaluation of the connection concepts was undertaken. Several issues related to concepts were address and research efforts to study these issues were initiated. With regard to bolted connections the primary issue leading to concerns of using bolts below the waterline is due to stress relaxation of the bolts causing a degradation of watertight integrity. Little or no information was found related to through the thickness creep response in Eglass/Vinylester composites due to environmental effects. A decision was made to embark upon a thorough study of this effect in parallel to other tasks in this program.

Similar issues were uncovered with regard to watertight integrity of adhesively bonded joints. Environmental influences are found to cause significant degradation in similar composites. Surface preparation is observed to have a significant influence on integrity of the bond. Little information is available on connections with relatively thick bondlines. Thicker bondlines are more typical of the manufacturing processes used in Naval vessels. A decision was made to embark upon a study to evaluate the mechanical properties of various adhesives with surface preparation, bondline thickness and environmental conditions as parameters.

Studies of the hydrodynamic response of vessels with underwater bodies uncovered the fact that cavitation may occur at higher speeds in excess of 50 knots. For this reason, a decision was made by the team to carry out a study of cavitation erosion protection. This study will be primarily a screening test that will attempt to identify the amount of cavitation erosion protection offered by various materials and surface treatments. During the initial screening, the erosion of various materials will be compared to the erosion of

standard materials using a relatively inexpensive ultrasonic setup. ATS will be the lead for this effort.

Progress was made in the area of structural monitoring. Attempts to develop techniques for embedment of curved sensors using piezoelectric materials were initiated. Typical piezoelectric patches used for sensors and actuators are flat and brittle. Novel piezoelectric patches that are flexible and allow for fabrication in curved geometries are currently being developed.

Use of fiber optics for sensors was also investigated. Fiber optic Bragg grating sensors allow for numerous sensors on one fiber optic strand. This has many advantages especially with regard to reduction of cabling requirements. Bragg sensing systems have also been developed with a more than adequate dynamic response for naval applications. Due to potential of using fiber optic cables as embedded sensors in composites, a study was embarked upon to assess embedment techniques, the function of the sensor, and the influence of the sensor on the structural response.

Planning was initiated for numerical analysis of connection models. It is imperative that nonlinear capability is included in connection models. Modeling of the stress relaxation in bolted connections was initiated. With regard to the bolted connections, viscoelastic response and contact are identified as the most significant nonlinearities. A decision was made that the ABAQUS computer code was a good tool for the computation studies. Test models were initiated to study creep in combination with contact so to quantify the stress relaxation of a bolted joint.

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14. ABSTRACT This progress report summarizes the first quarter of work on the Modular Advanced Composite Hullform (MACH) project. The primary tasks covered in this quarter are: 1) development of concepts and criteria for hybrid structures and connections; 2) develop criteria for structural monitoring system; and 3) further the design of the underwater body for the HYSWAC. Review of a connection evaluation are summarized along with identification of issues related to implementation of hybrid connections in underwater environments.						
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